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三内丸山 2℃寒冷化で滅ぶ

食料激減、縄文集落に打撃

東大教授ら調査

縄文時代に栄えた「三内丸山遺跡」(青森市)の集落が約4200年前に滅んだのは、2度の気温低下が原因だった可能性が高いことが、川幡穂高・東京大学教授(古気候学)らによる調査でわかった。それまで豊富だった食料用の木の実などが、この寒冷化で激減したらしい。

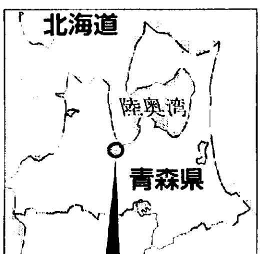
三内丸山遺跡は陸奥湾の南約3キロ・メートルにある、縄文時代最大規模の集落跡。約5900年前に成立し、約1700年後に消滅した。しかし、長期にわたる気候変動の詳しいデータがなく、集落の盛衰と気候の関連は不明だった。

川幡教授らは、この遺跡から約20キロ・メートル離れた陸奥湾で、水深61メートルの海底から堆積(たいせき)物を採取。プランクトンがどのような物質をつくっていたかを手がかりに、当時の海面水温を推定した。

その結果、海面水温は5900年前から約1700年かけて、約22度から約24度まで徐々に上昇したが、4200年前ごろ、約22度まで急激に低下した。気温の低下も、おなじ約2度とみられる。

堆積物中の花粉などを調べたところ、温暖期には陸上では食用に適したクリなどが多く育ち、海中には魚が多く生息できたが、寒冷化して、その環境が失われたことがわかった。

川幡教授によると、この寒冷化は、この地域に吹く南西からの暖かな季節風が弱まったことなどが原因らしい。川幡教授は「2度の寒冷化の影響は、思いのほか大きい。数度の温度変化でも、農業などの1次産業は大きな影響を受ける可能性がある」と話している。



三内丸山遺跡(青森市)

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Changes of environments and human activity at the Sannai-Maruyama ruins in Japan during the mid-Holocene Hypsithermal climatic interval

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ABSTRACT

Sannai-Maruyama is one of the most famous and best-researched mid-Holocene (mid-Jomon) archaeological sites in Japan, because of a large community of people for a long period. Archaeological studies have shown that the Jomon people inhabi1ted the Sannai-Maruyama site from 5.9 to 4.2 ± 0.1 cal kyr BP However, a continuous record of the terrestrial and marine environments around the site has not been available. Core KT05-7 PC-02, was recovered from Mutsu Bay, only 20 km from the site, for the reconstruction of high-resolution time series of environmental records, including sea surface temperature (SST). C_{37} alkenone SSTs showed clear fluctuations, with four periods of high (8.4–7.9, 7.0–5.9, 5.1–4.1, and 2.3–1.4 cal kyr BP) and four of low (–8.4, 7.9–7.0, 5.9–5.1, and 4.1–2.3 cal kyr BP) SST. Thus, each SST cycle lasted 1.0–2.0 kyr, and the amplitude of fluctuation was about 1.5–2.0 °C. Total organic carbon (TOC) and C_{37} alkenone contents, and the TOC/total nitrogen ratio indicate that marine biogenic production was low before 7.0 cal kyr BP, but was clearly increased between 5.9 and 4.0 cal kyr BP, because of stronger vertical mixing. During the period when the community at the site prospered (between 5.9 and 4.2 ± 0.1 cal kyr BP), the terrestrial climate was relatively warm. The high relative abundance of pollen of both *Castanea* and *Quercus* subgen. *Cyclobalanopsis* supports the interpretation that the local climate was optimal for human habitation. Between 5.9 and 5.1 cal kyr BP, in spite of warm terrestrial climates, the C_{37} alkenone SST was low; this apparent discrepancy may be attributed to the water column structure in the Tsugaru Strait, which differed from the modern condition. The evidence suggests that at about 5.9 cal kyr B.P, high productivity of marine resources such as fish and shellfish and a warm terrestrial climate led to the establishment of a human community at the Sannai-Maruyama site. Then, at about 4.1 ± 0.1 cal kyr BP, abrupt marine and terrestrial cooling, indicated by a decrease of about 2 °C in the C_{37} alkenone SST and an increase in the pollen of taxa of cooler climates, led to a reduced terrestrial food supply, causing the people to abandon the site. The timing of the abandonment is consistent with the timing (around 4.0–4.3 cal kyr BP) of the decline of civilizations in north Mesopotamia and along the Yangtze River. These findings suggest that a temperature rise of ~2 °C in this century as a result of global warming could have a great impact on the human community and especially on agriculture, despite the advances of contemporary society.

1. Introduction

The mid-Holocene is well known for having a warmer climate than the present. Currently, it is important to increase our understanding of modern climatic variability and its socioeconomic impacts as a function of increased concentrations of greenhouse

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gases. Although the Greenland Ice Sheet Project 2 reported that the Holocene climate was relatively stable (Dansgaard et al., 1993), high-resolution studies from the subpolar North Atlantic (Bond et al., 1997) and subtropical North Atlantic (deMenocal et al., 2000) have shown that sea surface temperatures (SSTs) document synchronous cooling events recurring at 1500 ± 500 year intervals throughout the Holocene.

The warm Holocene climate provided a good environment for people living in Japan. The population generally increased all over Japan from the Incipient to Middle Jomon periods (12.0–4.3 cal kyr BP; Kito, 2000) (Table 1), which corresponded approximately to the global mid-Holocene Hypsithermal climatic interval (Haug et al., 2001). In particular, around the Middle Jomon period (5.2–4.3 cal kyr BP), the total population in Japan reached a maximum, with many large communities. Then, after 4.3 ± 0.2 cal kyr BP, the population apparently declined, with fewer, and smaller communities (Kito, 2000).

The Sannai-Maruyama site, which is at the northern end of Honshu Island, Japan, is one of the most famous and well-studied mid-Holocene archaeological sites in Japan (Fig. 1a, b). Radiocarbon dating results and archaeological evidence such as excavated potsherds and the remains of pit dwellings indicate that people first settled here about 5.9 ± 0.1 cal kyr BP The population at the site then gradually increased before collapsing suddenly at $\sim 4.2 \pm 0.1$ cal kyr BP (Tsuji and Nakamura, 2001; Aomori Prefecture, 2002). The reason for the collapse remains unknown.

Outside of Japan, the north Mesopotamian civilization (4.2 cal kyr BP; Weiss et al., 1993) and the Yangtze River civilization (Shijiahe culture in 4.2–4.0 cal kyr BP, Yasuda et al., 2004) also declined at about the same time. So far, it is believed that the most critical reason behind them is a prolonged drought. The Akkadian, Maya, Mochica, and Tiwanaku civilizations also collapsed due to a severe aridity (deMenocal, 2001; Haug et al., 2003). Although cooling may be pointed as another factor, most discussion is unfortunately based on a qualitative, rather than quantitative, data set.

A continuous record of terrestrial environments is difficult to reconstruct from terrestrial sediments or wetland because terrestrial sediments are often eroded and transported away by wind or water. In contrast, marine sediments often provide a continuous record of both marine and terrestrial environments in their sedimentary sequence. Therefore, a shallow-marine sediment core PC-02 was collected near (only 20 km) the Sannai-Maruyama site (Fig. 1b) to evaluate the influence of environmental change on human activities at the site. The advantages of this core were that (1) it contained a continuous record of both terrestrial and marine environments during mid-Holocene with quite high sedimentation rate (65 cm kyr^{-1}), making high-resolution analysis possible; and (2) precise, quantitative estimates such as C_{37} alkenone temperatures could be obtained from the core. We analyzed the major biogenic components, alkenone-derived SST, carbon isotopes of benthic foraminifera, and the relative abundances of pollen and spores in the core sediments, and obtained radiocarbon dates on mollusca and benthic foraminifera. Our aim was to reconstruct with high resolution both the marine and adjacent terrestrial environments and thus gain an understanding of the relationship between climatic and environmental changes and the rise and fall of the human population at the Sannai-Maruyama site.

2. Materials and methods

2.1. Study area and sediment samples

A piston core PC-02 (41°00′N, 140°46′E; water depth, 61 m; length, 865 cm) was recovered from Mutsu Bay during cruise KT05-7 of the R/V *Tansei* (Fig. 1b). From the surface to 786 cm, the core consisted of very dark, greenish gray homogeneous clay sediments with a thin sand layer at 606–596 cm, and it contained burrows, scattered molluscan shells, and sea urchin fragments. From 786 to 855 cm, the sediments comprised very dark, grayish brown sandy silt or silt intercalated with sand layers. From 855 to 865 cm, the sediments consisted of dark, olive gray, coarse sand.

Mutsu Bay, at the northern end of Honshu Island, Japan, is a shallow (average depth, 40 m) bay with an area of 1660 km^2 and a relatively flat floor (gradient $< 2°$). It opens onto the Tsugaru Strait (sill depth, 130 m), which connects the Japan Sea with the northwestern North Pacific (Fig. 1a). Monthly mean SSTs are 6–7 °C in

Table 1
Chronological summary of Jomon periods in Japan and the related events.

Age (cal kyr BP)	Period in Japan	Events of Sannai-Maruyama	Events of the Yantze River civilization	Events of the world
2.0	Beginning of Yayoi			
3.0	Beginning of Final Jomon			
4.0	Beginning of Late Jomon		Decline of Shijiahe culture	
4.2 ± 0.1		Abandon		Collapse of Mesopotamian civilization
4.5			Beginning of Shijiahe culture	
4.6		Construction of the large, size-pillared building		
5.0	Beginning of Middle Jomon	Largest clay figurine		
5.3			Beginning of Qujialing culture	
5.5			Beginning of Mesopotamian civilization	Beginning of Mesopotamian civilization
5.8 ± 0.1		Settlement	Beginning of the middle Daxi period	
6.0	Beginning of Early Jomon			
6.4			Beginning of the early Daxi period	
10	Beginning of Initial Jomon			
12	Beginning of Incipient Jomon			

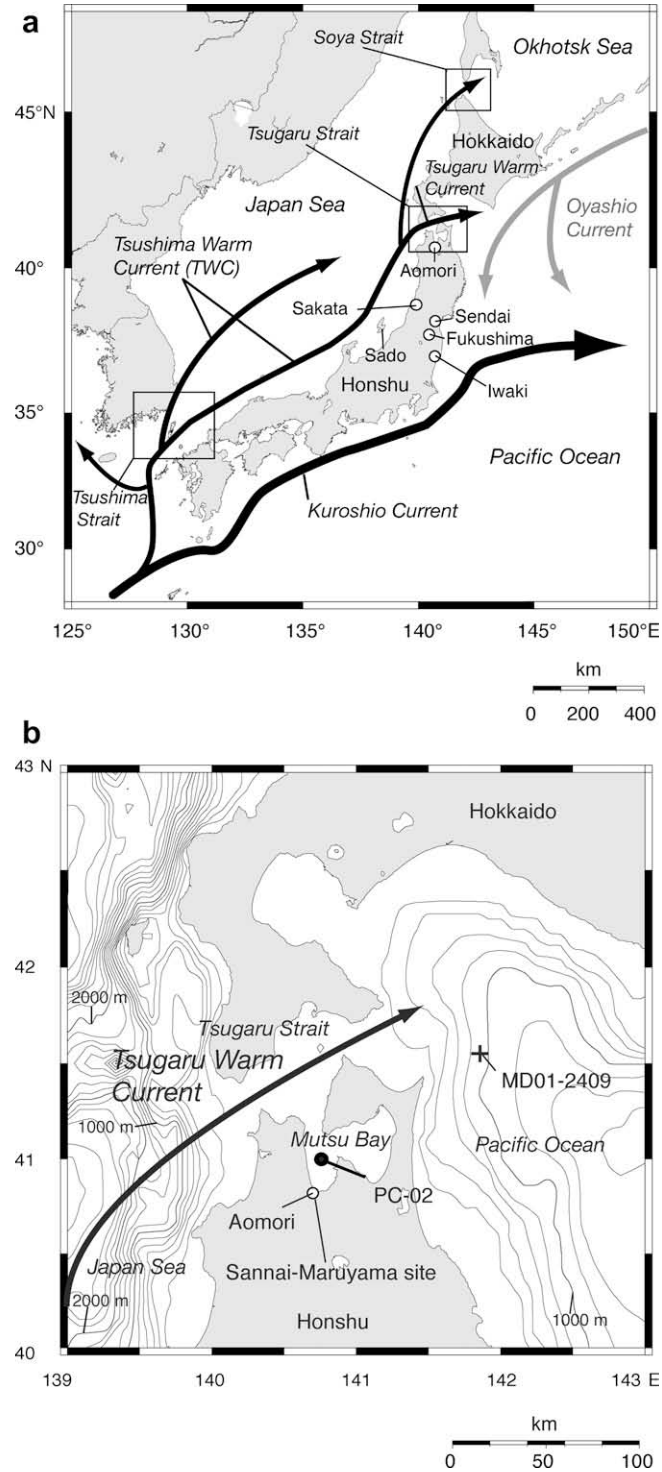

Fig. 1. (a) Map of the Japan Sea and the North Pacific around the Japanese Islands, including Honshu and Hokkaido. The paths of the Tsushima, Tsugaru, Oyashio, and Kuroshio currents are also shown. The route of the Kuroshio Current follows the figure by Jian et al. (2000). (b) Locations of the core KT05-7 PC-02 site (41°00′N, 140°46′E; water depth, 61 m) and the Sannai-Maruyama archaeological site. Bathymetric isolines are at 200 m depth intervals. The location (+) of the core MD01-2409 site (41°33.9′N, 141°52.1′E) is also shown.

February–March and 22–24 °C in August–September with the annual mean SST of 15 °C. During November–March, the uniform vertical profile reflects strong vertical mixing of the water column. Because only small rivers flow into Mutsu Bay, the salinity is 32.0–33.6 at the surface and 33.2–34.0 at 30 m depth, comparable to that in the Tsugaru Strait (32.0–34.6, Ozaki et al., 1991).

Recent meteorological data (1971–2000) collected at Aomori City (40°49′N, 140°45′E, about 20 km south of the core site) show monthly mean atmospheric temperatures of −1.4 °C in January and 23.0 °C in August with an annual mean value of 10.1 °C. Annual rainfall is 1290 mm, and the annual duration of solar irradiation is 1687 h. The land is snow covered for ~120 days each year. The wind direction is from the southwest most of the year, except for June (north) and August (east).

2.2. Fluctuation of the ocean environment around the Tsugaru Strait from glacial to interglacial times

The modern oceanographic setting of Mutsu Bay and the Tsugaru Strait is controlled mainly by the Tsugaru Warm Current (Fig. 1a, b), which is the main branch of the Tsushima Warm Current (TWC). Because the Tsugaru (sill depth, 130 m), Tsushima (130 m), Soya (55 m), and Mamiya (15 m) Straits are all narrow and shallow, there were drastic environmental changes in the Japan Sea from glacial to interglacial times. The estimated ice-equivalent sea level was about −130 m during the last glacial maximum (~21 kyr BP; Yokoyama et al., 2000a), causing the Japan Sea to be isolated from the open ocean (e.g., Oba et al., 1995; Yokoyama et al., 2007a). Subsequently, at ~17.5 cal kyr BP, the Oyashio Current started to enter the Japan Sea through the Tsugaru Strait under baroclinic transport conditions, which means that shallow and deep waters flowed through the strait in opposite directions because of the large difference in density between them (Ikeda et al., 1999). The TWC began to flow into the Japan Sea through the Tsushima Strait at ~11.5 cal kyr BP (e.g., Oba et al., 1995), and it began to flow out to the northwestern North Pacific through the Tsugaru Strait as the Tsugaru Warm Current at 10.6–8.3 cal kyr BP However, subsurface waters remained under the influence of the Oyashio Current (Takei et al., 2002; Kuroyanagi et al., 2006). The modern oceanographic regime was established at 6.2–4.8 cal kyr BP, when the subsurface waters began to warm as a result of the enhanced flow rate of the TWC (Kuroyanagi et al., 2006). Oscillations in the flow rate of the TWC during the Holocene have been correlated with global climatic fluctuations with a period of 1.5 kyr on the basis of diatom floras and planktonic foraminiferal and warm molluscan assemblages in the Japan Sea and the Okhotsk Sea (Shimada et al., 2004; Koizumi et al., 2006; Takata et al., 2006).

2.3. The Sannai-Maruyama archaeological site

Many archaeological sites from the Jomon period (12.0–2.0 cal kyr BP, in Japan) (Table 1) have been discovered on northeastern Honshu Island, including the area around Mutsu Bay. The Sannai-Maruyama site (40°49′N, 140°42′E; altitude, 17–20 m; Fig. 1b), about 3 km south of the bay, is the largest of these sites, with an estimated area of 350,000 m^2.

Recent archaeological studies have revealed that a large population with a well-developed culture inhabited the site. In addition to more than 40,000 boxes of pottery and stone implements, numerous remains of pit dwellings, burial pits, and buildings have been excavated. Moreover, many remains of animals and plants have been found in the valley to the north of the site, where water-saturated peat beds preserve organic remains well. Kitagawa and Yasuda (2004) suggested that some plants were cultivated to support the large population. In particular, chestnuts and horse chestnuts were likely important food sources at the site. Tsuji and Nakamura (2001) obtained accelerator mass spectrometry (AMS) radiocarbon dates on 90, mainly charcoal, samples from the site, which suggest that the site was inhabited for 1.6 kyr, from 5.9 to

4.3 ± 0.1 cal kyr BP Moreover, the Aomori local government obtained radiocarbon dates ranging from 4.30 to 4.17 ± 0.04 cal-kyr BP from a cross-section of a chestnut post (http://sannaimaruyama.pref.aomori.jp/english/index.html), suggesting that the people may have abandoned the Sannai-Maruyama site about 4.2 ± 0.1 cal kyr BP We adopted this latter date for the purpose of discussion in this study. Thereafter, the site remained uninhabited until the Heian Period (794–1192 AD).

2.4. Analytical procedures

For the foraminiferal and molluscan isotope measurements, sediment samples were freeze-dried, then disaggregated, wet-sieved through a 64-μm sieve, and dried at 40 °C. A total weight of <12 mg of molluscan shells and >9 mg of benthic foraminifera (mixed species) were picked for AMS radiocarbon dating at MALT (Micro Analysis Laboratory, Tandem accelerator, the University of Tokyo) (Table 2). The detailed procedure has been reported by Yokoyama et al. (2000b, 2007b). The results were corrected for the reservoir age in the Tsugaru Strait ($\Delta R = 34 \pm 42$) (Yoneda et al., 2007) and converted to calendar ages by using the INTCAL04 database (Reimer et al., 2004; Hughen et al., 2004) and the Calib 5.0.2 program (Stuiver et al., 2005). Calendar ages are expressed as cal kyr BP.

Benthic foraminifera were used for stable isotope measurements because planktonic foraminifera were not abundant enough in the shallow bay for the analysis. Forty to 50 specimens of *Nonionella stella* (Cushman) and 30 specimens of *Nonionellina labradorica* (Dawson) were picked. The detailed procedure was reported by Ohkushi et al. (2003). The analysis was conducted with an IsoPrime mass spectrometer fitted with an on-line automated carbonate preparation device (Micromass, UK) at the Japanese National Institute of Advanced Industrial Science and Technology (AIST). The analytical precision of this system is better than 0.05‰ for $\delta^{13}C$ (Suzuki et al., 2003). The values were calibrated against the U.S. National Institute of Standards and Technology (NIST) calcite standard (NBS-19) and are reported here as the per mil deviation relative to the Vienna Pee Dee Belemnite (VPDB) standard.

Sediment samples for chemical analyses were frozen on board ship and kept at −20 °C until analysis at the land-based laboratory. They were freeze-dried, crushed into fine powder, and split into two aliquots. One aliquot was used for the analysis of total carbon (TC), total organic carbon (TOC), total nitrogen (TN), and carbonate contents with a Yanako CHN Corder MT5 elemental analyzer at AIST, by analytical methods similar to those reported by Maeda et al. (2002). The powdered sample was weighed (30 mg) in a ceramic sample boat for the TC and TN measurements. For TOC determination, a portion of the dried sample was decalcified with a few drops of 1 N HCl. After 3 h, the sample was dried for at least 4 h at 80 °C to remove unreacted HCl and water. Carbonate content was calculated by using the formula, carbonate = (TC content − TOC content) × 8.333. The analytical error, based upon 5 replicate analyses, was within 0.8% for carbon (TC and TOC), and within 4.6% for TN.

The second aliquot was used for alkenone analysis by the method described by Harada et al. (2003). Three grams of powdered sample were extracted with dichloromethane and methanol (99:1 v/v) in an accelerated solvent extractor (ASE-200, Dionex Japan, Ltd.) at 100 °C and 1000 psi. To quantify the C_{37} alkenones and estimate the recovery efficiency of the extraction, a ketone standard (2-nonadecanone) was added to the sample. The extract was saponified with 0.5 M KOH/methanol at 80 °C for 2 h. The neutral fraction, isolated by extraction with hexane, was divided into subfractions by silica-gel column chromatography using an automatic solid-phase extraction system (Rapid Trace SPE Workstation, Zymark, UK). C_{37} alkenones were eluted with *n*-hexane for fraction 1: hexane/toluene (3:1 v/v), hexane/toluene (1:1 v/v), hexane–ethyl acetate (95:5 v/v), and hexane–ethyl acetate (9:1 v/v) for fraction 2; and hexane–ethyl acetate (85:15 v/v) and hexane–ethyl acetate (4:1 v/v) for fraction 3. The C_{37} alkenone fraction was analyzed by capillary gas chromatography with a Hewlett Packard 6890 series gas chromatograph equipped with an on-column injector, a Chrompack CP-Sil 5CB fused silica column (50 m × 0.32 mm internal diameter), and a flame ionization detector, at AIST. Several procedural blanks, which were analyzed in parallel with the sample analyses, showed no C_{37} alkenone contamination. The analytical error for $U_{37}^{K'}$ (defined as [37:2]/([37:2] + [37:3])) was ±0.0060, and that for the C_{37} alkenone content was <20%, based on 5 replicate analyses. As pointed out by Villanueva and Grimalt (1997), irreversible adsorption of $C_{37:3}$ on the chromatographic column is often a major source of error when the total amount of C_{37} alkenone injected into the system for analysis is <5 ng. Therefore, the error should be minimized in this study by <5 ng in each injection.

In this study, SSTs were calculated by assuming a linear relationship between SST and C_{37} alkenone unsaturation and using the empirical equation reported by Müller et al. (1998): $U_{37}^{K'} = 0.033\,T\,(°C) + 0.044$.

C_{37} alkenone fluxes were calculated from the C_{37} alkenone content, dry bulk density (DBD), and sedimentation rate as follows: alkenone flux ($\mu m\,cm^{-2}\,kyr^{-1}$) = alkenone content ($\mu m\,g^{-1}$) × DBD ($g\,cm^{-3}$) × sedimentation rate ($cm\,kyr^{-1}$).

Pollen and spores were analyzed by the method of Kawahata and Ohshima (2002). To calculate the relative abundance of pollen and spores in sediments (grains g^{-1}), ∼1 g of a freeze-dried aliquot was weighed, and then 10% HCl was added to dissolve carbonates followed by HF treatment to remove siliceous matter. After density separation with $ZnBr_2$, the samples were treated by Erdtman's acetolysis method and with 10% NaOH. Microfossil slides of the treated material were prepared by mounting in glycerin jelly. The palynological analyses were carried out under a Nikon Optiphot-2 microscope at magnifications of ×150 and ×600. At least 253 grains

Table 2
Sampled species, core depths and results of radiocarbon dating.

Sample type	Specific name	Sample #	Depth (cm)	^{14}C age (yrs BP)	Calendar age (cal yrs BP)
Mollusca	*Mizuhopecten yessoensis* (Jay)	1–2	3.3	1080 ± 80	606 ± 70
Mollusca	*Mizuhopecten yessoensis* (Jay)	2–6	27.5	4030 ± 100	3998 ± 151
Benthic foraminifera	Mixed species	2–6	27.5	4170 ± 90	4213 ± 142
Mollusca	*Leionucula tenuis* (Montagu)	2–43	111.5	4930 ± 90	5177 ± 143
Mollusca	*Ringiculina doliaris* (Gould)	3–28	177.4	5600 ± 110	5984 ± 145
Benthic foraminifera	Mixed species	3–28	177.4	5610 ± 100	5992 ± 131
Mollusca	*Mizuhopecten yessoensis* (Jay)	4–15	248.6	6160 ± 120	6552 ± 144
Mollusca	*Mercenaria stimpsoni* (Gould)	5–39	403.9	7830 ± 110	8264 ± 118
Mollusca	*Raetellops pulchellus* (Adams & Reeve)	8–6	633.9	9450 ± 90	10280 ± 111
Mollusca	*Macoma* cf. *tokyoensis* (Makiyama)	8–25	674.5	9490 ± 90	10313 ± 108

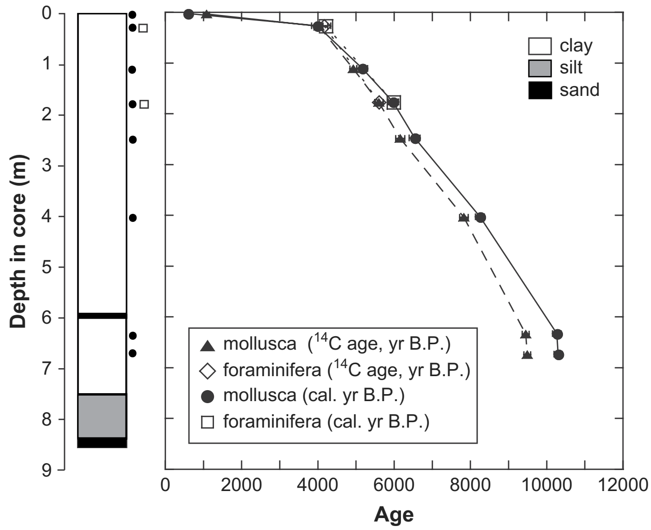

Fig. 2. Core depth versus radiocarbon (a) and calendar (b) ages, and a profile of the core. ^{14}C ages based on benthic foraminifera were converted to calendar ages by using a reservoir age correction of 630 years. Linear sedimentation rate data (cm kyr^{-1}) are also shown.

(380 grains on average) of pollen and spores were counted for each sample. Percentage values of each taxon were calculated in relation to the sum of the arboreal and nonarboreal (shrub and herb) pollen.

3. Results

3.1. Radiocarbon dating and sedimentation rate

The upper 675-cm-long section of core PC-02 provides a continuous environmental record for the last 10.3 kyr, as seen in both the radiocarbon and corrected calendar age–depth profiles (Fig. 2, Table 1). The difference in calendar ages between dates on molluscan shells and those on benthic foraminiferal tests from the two horizons at 27.5 and 177.4 cm depth were very small (200 and 8 years, respectively), suggesting that reworking of sediments was minimal in core PC-02. The age model in this study was therefore obtained by linear interpolation between molluscan radiocarbon dated horizons. The mean sedimentation rate was 65.4 cm kyr^{-1}, which is consistent with the rate of 85 cm kyr^{-1} determined using ^{210}Pb measurements of offshore mud deposits in Mutsu Bay (Hayashi, 1988). The sedimentation rate in the top 28 cm of sediments was 7.1 cm kyr^{-1}, in contrast to an average rate of 102.5 cm kyr^{-1} in the deeper part of the core. DBD ranged from 0.33 to 1.09 g cm^{-3} with a mean value of 0.61 g cm^{-3}. It generally increased with depth because of compaction of the sediments. A high DBD value (1.04 g cm^{-3}) was obtained for the thin sand layer at 598–601 cm (10.0 cal kyr BP).

3.2. Sedimentation of biogenic components

TOC and TN constituted 0.90–2.38 wt% and 0.09–0.27 wt% of the sediments, averaging 1.36 wt% and 0.14 wt%, respectively (Fig. 3, data stored in a paleo-data bank, www.pangaea.de).[1] Both values were somewhat high until ∼9.0 cal kyr BP, became low from ∼9.0 to 7.0 cal kyr BP, increased slightly from 7.0 to 5.9 cal kyr BP, and then moderately from 5.9 to 5.0 cal kyr BP, after which they increased continuously to the present. TOC/TN atomic ratios ranged from 10.0 to 13.1 (average, 11.3); they were somewhat low between 9.0 and 6.7 cal kyr BP (average, 10.9) and then increased after 6.7 cal kyr BP The TOC/TN atomic ratio of organic matter is a useful proxy for evaluating the origin of organic matter in marine sediments. Typical sedimentary marine organic matter has a TOC/TN ratio of 8–9 whereas the TOC/TN ratio in terrestrial organic matter ranges from about 20 to 200 (Hedges and Parker, 1976). According to the results from river to coastal marine environments, OC in typical marine environments near Nagoya City, Japan, demonstrated similar feature, namely moderate to low TOC/TN ratios (9.0–10.7) with higher $\delta^{13}C$ of OC. (Nakai et al., 1982). The moderate to low TOC/TN ratios in core PC-02 indicate that most organic matter was of marine origin, with only a small contribution of terrestrial organic matter during the Holocene, despite the nearness of the site to land.

The carbonate content in core PC-02 was generally low (0.23–4.23 wt%; avg., 1.66 wt%) compared with that in the northwestern North Pacific. Optical microscope observations showed that mollusca, sea urchins, benthic foraminifera, and ostracods were major contributors to biogenic carbonate in core PC-02, except during the early Holocene. An interesting feature of core PC-02 is that the TOC, TN and carbonate contents and the TOC/TN atomic ratios showed relatively similar profiles. In general, values were high but variable until 9.0 cal kyr BP, low between 9.0 and 6.7 cal kyr BP, and then increasing after 6.7 cal kyr BP.

3.3. C_{37} alkenone SST

C_{37} alkenones in the ocean are derived mainly from the prymnesiophyte coccolithophorids *Emiliania huxleyi* (Volkman et al., 1980) and *Gephyrocapsa oceanica* (Marlowe et al., 1984). Prahl et al. (1988) proposed that paleotemperatures could be estimated from $U^{K'}_{37}$ on the basis of culture experiments with *E. huxleyi*, and Conte et al. (1998) pointed out that *E. huxleyi* or *G. oceanica* yielded substantially different $U^{K'}_{37}$–SST relationships. C_{37} alkenone SSTs deduced from *G. oceanica* culture experiments are higher than those deduced from *E. huxleyi* cultures (Volkman et al., 1980). However, a global core-top calibration based on data of both *E. huxleyi* and *G. oceanica* from 370 sites between 60°S and 60°N in the Pacific, Atlantic, and Indian Oceans, by Müller et al. (1998), is identical within error limits to the widely used *E. huxleyi* culture calibration of Prahl et al. (1988). These results reported by Müller et al. (1998) suggest that in the field, $U^{K'}_{37}$ is less species dependent than is indicated by culture experiments. The analysis of the coccoliths in core PC-02 showed both *G. oceanica* and *E. huxleyi* to be dominant species in Mutsu Bay (Dr. Y. Tanaka, personal communication). The relative abundance of *G. oceanica* in the core was 47–91% (average, 73) and that of *E. huxleyi* was 5–49% (average, 22%), and the small fluctuations in these relative abundances throughout the core did not correlate with variations in the C_{37} alkenone SSTs. These findings imply that changes in the coccolithophorid floral assemblage were not mainly responsible for those in C_{37} alkenone SSTs in core PC-02 (Müller et al., 1998).

Year-long sediment-trap experiments carried out at site MD01–2409 (41°33.8′, 141°52.0′E), which is influenced by only the Tsugaru Warm Current, have shown that the modern coccolithophore production season is mainly June–August (Ishizaki et al., 2003). This observation coincides with the seasonal change of chlorophyll-*a* concentrations in the surface ocean in this area. Therefore C_{37} alkenone SSTs would record the SST in summer when present SST is around 22 °C.

The C_{37} alkenone SSTs in core PC-02 fluctuated from 19.4 °C to 24.2 °C (average, 22.9 °C). The 10-kyr record can be classified into 9

[1] Data of sampled core depths, ages, dry bulk densities, $U^{K'}_{37}$, sea surface temperatures (SST) and contents of C_{37} alkenone and major chemical components; specimen, and $\delta^{13}C$ of *Nonionella stella* and *Nonionellina labradorica*; and occurrence of pollen and spores in the studied cores are stored in a paleo data-bank (www.pangaea.de).

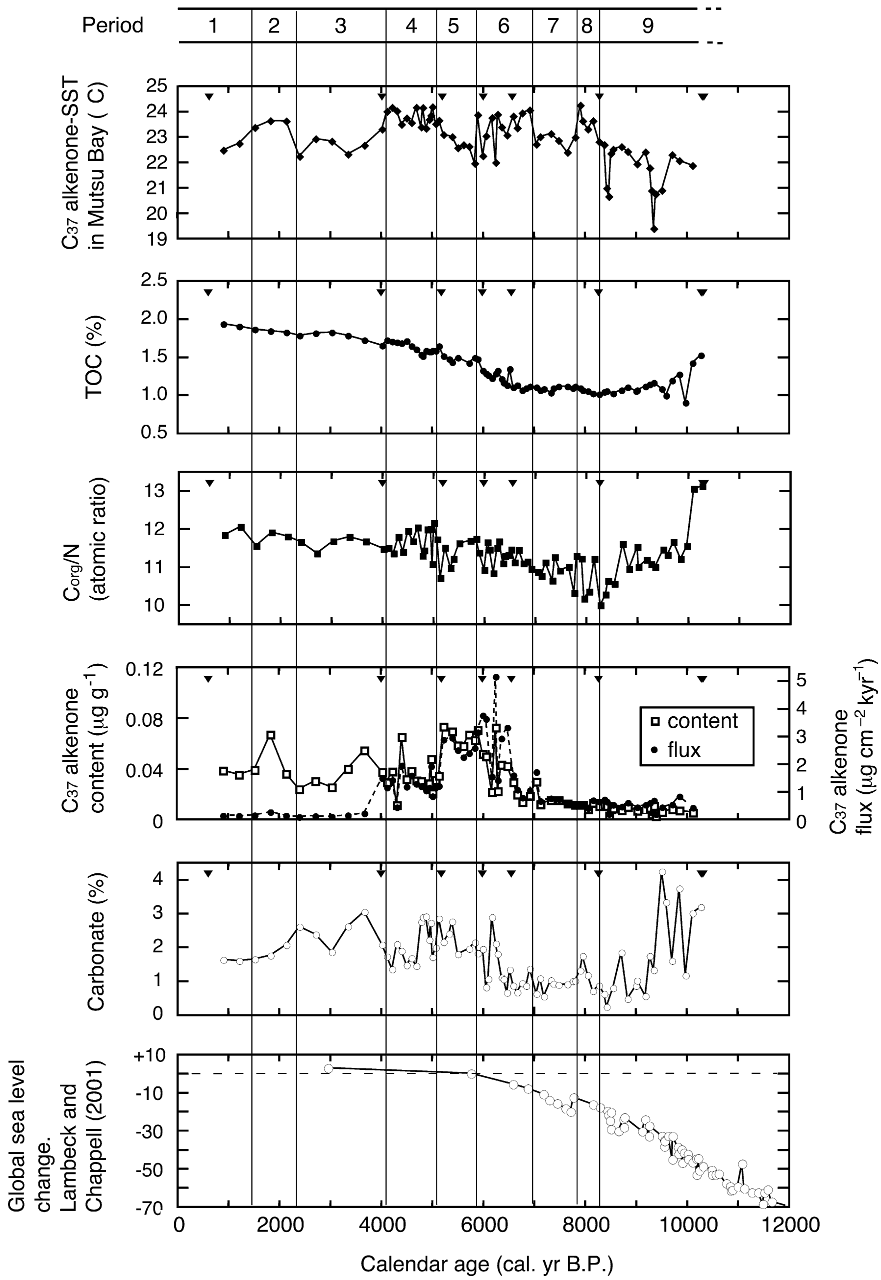

Fig. 3. Time series records of (a) C_{37} alkenone SSTs, (b) TOC content, (c) TOC/TN ratio, (d) C_{37} alkenone content, and (e) carbonate and global sea level change (Lambeck and Chappell, 2001).

periods on the basis of changes in the C_{37} alkenone SST. Periods 8 (8.3–7.9 cal kyr BP), 6 (7.0–5.9 cal kyr BP), 4 (5.1–4.1 cal kyr BP) and 2 (2.3–1.4 cal kyr BP) were characterized by warm alkenone SSTs with mean values of 23.4, 23.4, 23.8, and 23.5 °C, respectively. In contrast, periods 9 (–8.3 cal kyr BP), 7 (7.9–7.0 cal kyr BP), 5 (5.9–5.1 cal kyr BP), and 3 (4.1–2.3 cal kyr BP) were characterized by cold alkenone SSTs with mean values of 21.6, 22.8, 22.9, and 22.7 °C, respectively (Fig. 3, data stored in a paleo-data bank, www.pangaea.de).

3.4. C_{37} alkenone abundance

C_{37} alkenone content ranged from 0.0004 to 0.105 $\mu g\, g^{-1}$, averaging 0.030 $\mu g\, g^{-1}$ (Fig. 3, data stored in a paleo-data bank, www.pangaea.de). The values were low at the bottom of the core, but gradually increased until 7.0 cal kyr BP; they were high between 7.0 and 5.2 cal kyr BP, and moderate after 5.2 cal kyr BP The C_{37} alkenone flux also began low but then gradually increased from 10.0 to 7.0 cal kyr BP; it increased abruptly at 7.0 cal kyr BP, was high between 7.0 and 5.2 kyr BP, and then decreased to moderate values between 5.2 and 4.0 cal kyr BP The flux was very low in the upper 28 cm of the core (4.0 cal kyr BP to the present) owing to the low sedimentation rate.

3.5. Pollen and spores

The result of pollen and spores in core PC-02 are shown in Fig. 4 (data stored in a paleo-data bank, www.pangaea.de). Forty-four species of arboreal pollen, 28 species of nonarboreal pollen, and 4 species of Pteridophyta and Bryophyta spores were identified. Total abundance of pollen and spores varied from 14.6×10^3 to 73.4×10^3 grains g^{-1} (average, 34.6×10^3 grains g^{-1}), which is

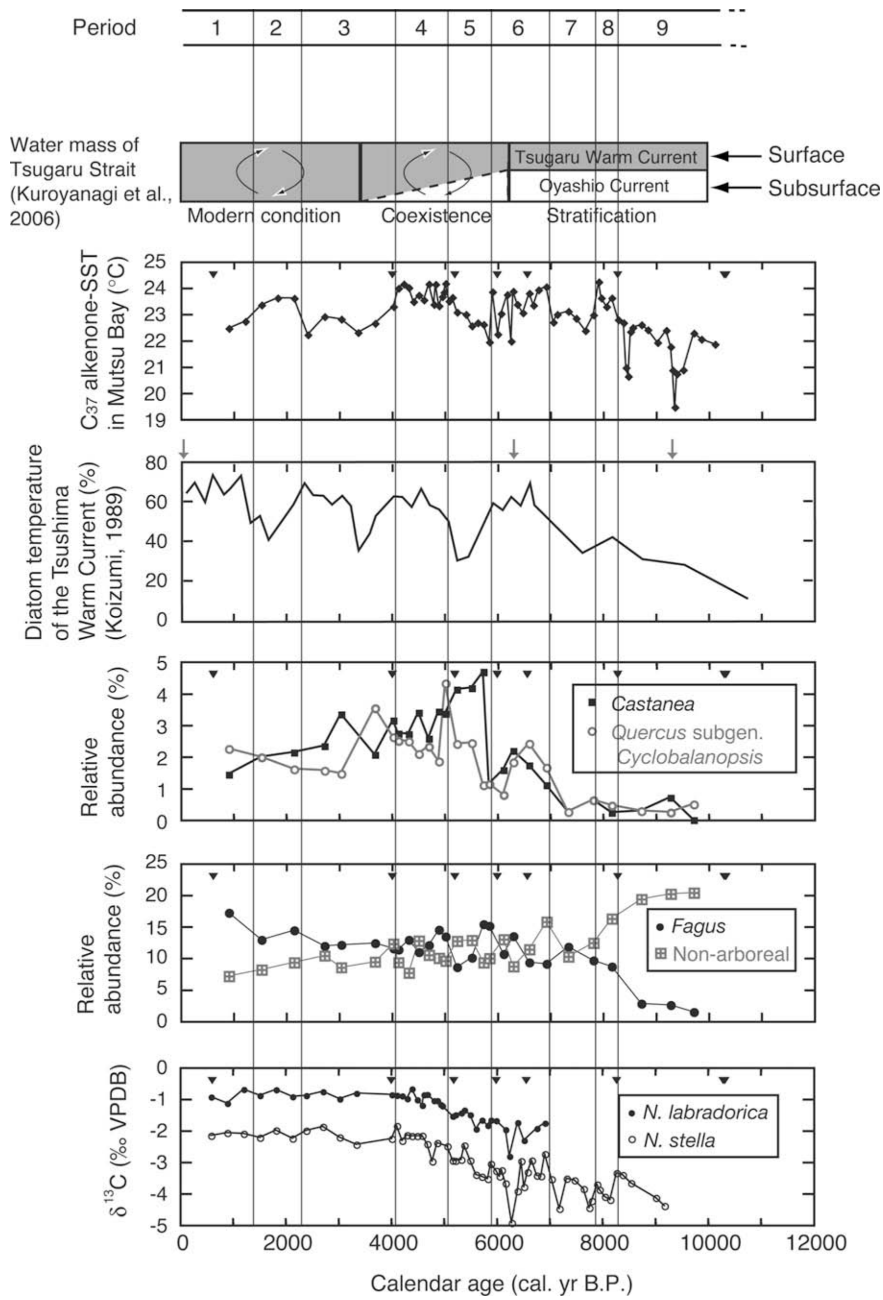

Fig. 4. Time series records of (a) C_{37} alkenone SSTs, (b) diatom temperature of the Tsushima warm current (Koizumi, 1989), (c) relative abundances of *Castanea* and *Quercus* subgen. *Cyclobalanopsis*, (d) relative abundances of *Fagus* and nonarboreal pollen, (e) $\delta^{13}C$ values of benthic foraminiferal tests (*Nonionella stella* (Cushman) and *Nonionellina labradorica* (Dawson)). The water column structure of the Tsugaru Strait as reconstructed by Kuroyanagi et al. (2006) is also shown.

approximately 3 orders of magnitude higher than their abundance in the open ocean (Kawahata et al., 2002). Pollen and spore abundances were low until 5.9 cal kyr BP, and then gradually increased to modern levels. The downcore variation in pollen and spores reflects terrestrial environmental changes over the past 10 kyr.

Before ∼8.4 cal kyr BP, broadleaf deciduous pollen was dominant: *Quercus* subgen. *Lepidobalanus* predominated, followed by *Betula*, *Alnus*, *Carpinus-Ostrya*, and *Cercidiphylum*. Conifer pollen such as *Picea* and Taxaceae–Cephalotaxaceae–Cupressaceae showed relative high abundances. *Fagus* occurred with low abundance. Nonarboreal pollen, including *Gramineae*, *Cyperaceae*, and *Artemisia*, was relatively high in abundance. After ∼8.5 cal kyr BP, broadleaf deciduous pollen such as *Quercus* subgen. *Lepidobalanus* and *Fagus* were dominant, followed by *Juglans*, *Alnus*, *Carpinus-Ostrya*, and *Cercidiphylum*. The relative abundance of *Fagus* increased suddenly at ∼8.4 cal kyr BP, similar to results reported by a study from the northern end of Honshu Island (8.5 ± 0.2 cal kyr BP; Tsuji et al., 1983). *Picea*, *Betula*, and *Cercidiphylum*, which are proxies for a relatively cold subarctic climate, all gradually decreased beginning at about 8.5 cal kyr BP The relative abundances of *Lepidobalanus* and *Fagus* showed broad maxima between ∼7.5 and 4.1 cal kyr BP, indicating that the regional climate was warm during this period. This inference is supported by the higher relative abundance of *Cyclobalanopsis* and *Castanea* between 7.0 and ∼4.1 cal kyr BP *Cyclobalanopsis* is an important taxon in warm-temperature evergreen broad-leaved forests. Its modern northern limit of occurrence is on Sado Island in the Japan Sea, and at Iwaki on the Pacific coast of Japan (Kawahata et al., 2003). *Castanea* is also indicative of a warm climate (e.g., Kitagawa and Yasuda, 2004). Beginning at about 4 cal kyr BP, the regional climate became cooler.

A high relative abundance of nonarboreal pollen and *Fagus* pollen may indicate low and high precipitation, respectively. Nonarboreal pollen decreased at around ∼8.5 cal kyr BP and remained low until the present. Moreover, *Fagus* thrives under wetter conditions than *Quercus* subgen. *Lepidobalanus* does (Tsuji et al., 1983). The ratio of *Fagus* to *Quercus* subgen. *Lepidobalanus* pollen abundances increased at around ∼8.5, suggesting that precipitation may have increased at that time.

3.6. Carbon isotopic values of benthic foraminifera

$\delta^{13}C$ values of *N. stella* ranged from −4.9‰ to −1.9‰, averaging −3.1‰ (Fig. 4, data stored in a paleo-data bank, www.pangaea.de). Although the data show considerable variability, $\delta^{13}C$ was low from ∼9.2 to 7.0 cal kyr BP and somewhat higher from 7.0 to 5.9 cal kyr BP It gradually increased from 5.9 to 4.1 cal kyr BP and then remained relatively constant until the present. Although the occurrence of *Nonionellina labradorica* was limited to the period after ∼7.0 cal kyr BP, its $\delta^{13}C$ profile was quite similar to that of *N. stella*, although the values were offset. Therefore, $\delta^{13}C$ values of benthic foraminiferal tests may record environmental changes.

4. Discussion

4.1. Cyclic fluctuation of C_{37} alkenone SSTs during the Holocene

Temperature is one of the most important parameters controlling the environment. High-resolution reconstruction of the C_{37} alkenone SSTs in Mutsu Bay showed that the SST clearly fluctuated with a mean amplitude of ∼1.5–2.0 °C over the last 10 kyr; the high-SST periods were 8.3–7.9, 7.0–5.9, 5.1–4.1, and 2.3–1.4 cal kyr BP, suggesting a cycle duration of 1.0–2.0 kyr (Figs. 3 and 4).

Because the seawater properties in Mutsu Bay are determined mainly by the Tsugaru Warm Current, a branch of the TWC, fluctuations in the intensity of the TWC presumably affected SSTs in the bay. Paleoceanographic conditions around the Tsugaru Strait since 30.0 cal kyr BP have been reconstructed from an analysis of the diatom assemblages in six piston cores collected from the Japan Sea and the northwestern North Pacific (Koizumi, 1989; Koizumi et al., 2006). The results suggest that the flow intensity of the TWC has fluctuated at ∼1.5-kyr intervals since 9.5 cal kyr BP in spite of low time resolution. Warm and cold periods deduced from C_{37} alkenone SSTs clearly correspond to those indicated by these diatom-based SSTs between 9.5 and ∼2 cal kyr BP, (maxima at around 8.1, 6.5, 4.5, and 2.2 cal kyr B.P, Koizumi, 1989) within error (Fig. 4). In particular, warm period 6 (7.0–5.9 cal kyr BP) in Mutsu Bay corresponded to the mid-Holocene Hypsithermal climatic interval. The mean C_{37} alkenone SSTs in warm periods 8, 6, 4, and 2 all fall within the small range of 23.4–23.8 °C.

4.2. Fluctuation of biogenic production and related marine environments

TOC is often used as a good indicator of biogenic productivity. C_{37} alkenone content also reflects *E. huxleyi* and *G. oceanica* productivity. TOC content was very low before 7.0 cal kyr BP, increased slightly from 7.0 to 5.9 cal kyr BP, moderately from 5.9 to 5.0 cal kyr BP, and then gradually until the present (Fig. 3). In spite of its generally similar profile, fluctuations in C_{37} alkenone content were more drastic. C_{37} alkenone content was very low and slightly increasing before 7.0 cal kyr BP, showed great variability but a general increasing trend from 7.0 to 5.9 cal kyr BP, was high from 5.9 to 5.0 cal kyr BP and moderately high from 5.0 to 4.0 cal kyr BP, and then fluctuated greatly until the present (Fig. 3). These characteristics are more evident when these data are compared with mass accumulation rates. Relatively high carbonate values before 9.0 cal kyr BP might reflect the different marine conditions, because the sea floor depth in Mutsu Bay would have been very shallow at that time because of the global lower sea level (30–40 m) (Lambeck and Chappell, 2001). Carbonate content was also high between 5.9 and 4.8 cal kyr BP (Fig. 3).

TOC in core PC-02 is a mixture of marine and terrestrial organic carbon. However, the moderate to low TOC/TN ratios (10.0–12.0) in the core suggest that most of the organic matter in it is of marine origin. However, small contribution (<10%) of terrestrial organic carbon may be expected, assumed that terrestrial OM has TOC/TN ratio of >20 (Hedges and Parker, 1976). Therefore marine biogenic production was low before 7.0 cal kyr BP and clearly increased between 5.9 and 4.0 cal kyr BP Marine plankton was not served directly as food by the people living at the Sannai-Maruyama site. However, higher primary production is generally associated with higher production of fish and seaweed, both of which were important sources of nutrition for these people (Aomori Prefecture, 2002). Therefore, marine products likely rapidly increased at Sannai-Maruyama site from 5.9 to 4.0 cal kyr BP.

Changes in biogenic production are often associated with changes in marine environmental conditions. The $\delta^{13}C$ values of benthic foraminiferal tests in core PC-02 are obviously lower than those of benthic foraminiferal tests from the open sea, such as the Japan Sea and the northwestern North Pacific (e.g., Oba et al., 1991; Hoshiba et al., 2006). Similar low values have been reported from inner bays and fjords (e.g., van Breugel et al., 2005). A shift to more negative $\delta^{13}C$ values in benthic foraminifera is often considered to reflect the presence of ^{13}C-depleted dissolved inorganic carbon formed by the degradation of organic matter (van Breugel et al., 2005). Therefore, low $\delta^{13}C$ values suggest a fairly stratified water column owing to restricted vertical circulation, such as is observed in a drowned valley. The general increasing trend of $\delta^{13}C$ values from ∼9.0 to 4.0 cal kyr BP might indicate a progressive increase in vertical mixing, culminating in the collapse of the stratification at about 4.0 cal kyr BP and the introduction of modern marine conditions (Fig. 4). These changing conditions may be related to changes in oceanographic conditions such as flow rate intensity or stratification in the Tsugaru Strait and adjacent areas. Kuroyanagi et al. (2006) reported low chlorophyll concentrations caused by stratification during 9.0–6.2 cal kyr BP on the eastern side of the Tsugaru Strait (Fig. 4). At that time, the intensity of the TWC was weak and the subsurface water remained under the influence of the cold Oyashio Current. It is well known that seasonal changes in water circulation in Mutsu Bay are much affected by changes in the flow rate of the Tsugaru Warm Current. At present, a higher intensity of the Tsugaru Warm Current leads to better circulation in Mutsu Bay. Therefore, a weaker TWC intensity and stratification of the water column may have reduced the circulation rate and thus the input of nutrients to the surface water in Mutsu Bay. Results from site MD01-2409 suggest that stronger vertical mixing of both the warm TWC and cold Oyashio waters started to occur at 5.9 cal kyr BP (Kuroyanagi et al., 2006); this mixing may have led to the enhanced production of C_{37} alkenones in Mutsu Bay in 5.9–4.0 cal kyr BP Even after 4.0 cal kyr BP, biogenic production remained relatively elevated, judging from the TOC content and the $\delta^{13}C$ values of benthic foraminiferal tests.

4.3. Influence of environmental change on human activities at the Sannai-Maruyama site

Here, we focus on the relationship between the record of human activity at the Sannai-Maruyama site and the terrestrial and marine environmental changes. Recent analyses of pollen from the Sannai-

Maruyama site (e.g., Tsuji, 1995; Kitagawa and Yasuda, 2004) and from the surrounding area (e.g., Tsuji et al., 1983; Yoshida, 2006) have shown that the flora changed from broad-leaved deciduous forests (mainly, *Fagus* and *Quercus* subgen. *Lepidobalanus*) to groves of *Castanea* (chestnut) and *Juglans* (walnut) trees at 5.9 cal kyr BP (the time that the human community was established), and then returned to broad-leaved deciduous forest at 4.3 cal kyr BP (near the time of abandonment of the settlement). Because a large amount of *Castanea* pollen was found at the site during the period of human habitation (5.9–4.2 $\pm$ 0.1 cal kyr BP), Kitagawa and Yasuda (2004) and Yasuda et al. (2004) proposed that some plants such as *Castanea* may have been cultivated, to some extent supporting the large population there during 5.9–4.2 $\pm$ 0.1 cal kyr BP, and that climatic cooling subsequently damaged the chestnut harvest and led to the decline of the human community. However, data from pollen and spores excavated at the site, or obtained from wetlands near the site, might be fairly biased by human activities such as cultivation and reclamation.

One of the interesting features of the Sannai-Maruyama site is that during 5.9–4.2 $\pm$ 0.1 cal kyr BP, the mid-Holocene Hypsithermal climatic interval, the human community experienced warm terrestrial conditions. It is consistent with higher C_{37} alkenone production. Although the reason behind relatively cold C_{37} alkenone SSTs during 5.9–5.1 cal kyr BP remain currently unclear, it is plausible that the water column structure in the Tsugaru Strait before ~5.0 cal kyr BP was more stratified than at present (Kuroyanagi et al., 2006), which may affect the seasonal shift of the alkenone production. These factors might explain the coexistence of a warm terrestrial climate and low C_{37} alkenone SSTs between 5.9 and 5.1 cal kyr BP.

Food supply is a crucial factor for human activities. When human habitation began at the Sannai-Maruyama site, the population was probably relatively small and it increased over time. The marine and terrestrial records of core PC-02 indicate that marine biological productivity greatly increased beginning in 5.9 cal kyr BP (Fig. 3). In general, the increase in $\delta^{13}C$ values of benthic foraminifera suggests that vertical mixing of seawater in Mutsu Bay increased at that time. It further suggests that an increase in the TWC flow intensity enhanced in greater lateral and vertical circulation of seawater in the bay and would also have supplied moisture to northern Honshu Island. Greater moisture is consistent with the sudden increase in the abundance of *Castanea* and *Quercus* subgen. *Cyclobalanopsis* pollen in core PC-02 (Fig. 4). Therefore, the great step up in marine production (fishes and shells) and terrestrial production (chestnuts and walnuts) resulted in an abundant food supply for a human community, leading to the establishment of the settlement at the Sannai-Maruyama site.

During the period when the community prospered (between 5.9 and 4.2 $\pm$ 0.1 cal kyr BP), the terrestrial climate improved and became generally warm and stable (Fig. 4). At Sannai-Maruyama site, numerous amounts of fruit seeds, such as wild grapes and actinidia, large seeds, such as chestnuts, Japanese walnuts and buckeyes, and the majority of mammal bones, such as rabbits and flying squirrels, were found. These are consistent with high relative abundance of pollen of both *Castanea* and *Quercus* subgen. *Cyclobalanopsis* in core PC-02. These lines of evidence support the interpretation that the local climate was optimal for the human community, which would have allowed the population to increase.

C_{37} alkenone SSTs suddenly dropped by ~2 °C at 4.1 cal kyr BP, and the relative pollen abundance of both *Castanea* and *Quercus* subgen. *Cyclobalanopsis* also started to decline in the middle of period 3. At present, a difference in atmospheric annual mean temperature of 2 °C corresponds to the latitudinal distance of about 220 km between Aomori City and Sakata City, on the Japan Sea coast, and Sendai City on the Pacific coast (Fig. 1a). Strikingly, a 2 °C difference in SST corresponds to the same distance. This is also valid to seasonal SST change between these locations. The northern limit of commercial chestnut (*Castanea*) cultivation in Japan is currently Fukushima Prefecture. Of course, *Castanea* pollen can be produced in a cooler climate, but the trees will not produce their edible fruit (chestnuts). Therefore, a cooling of 2 °C would have caused difficult living conditions at Sannai-Maruyama. The age of a chestnut post ranged from 4.30 to 4.17 $\pm$ 0.04 cal kyr BP (http://sannaimaruyama.pref.aomori.jp/english/index.html), implying that people abandoned the Sannai-Maruyama site as late as 4.1 cal kyr BP.

These results support the hypothesis that a shortage of food caused by climatic cooling caused people to abandon the Sannai-Maruyama site and to move elsewhere and form smaller communities. The TOC and C_{37} alkenone contents indicate that marine biological production in Mutsu Bay remained high, and even increased at around 4.2 $\pm$ 0.1 cal kyr BP Therefore, marine products from Mutsu Bay were not a major factor in the decline of the Sannai-Maruyama community.

4.4. Implications for climatic influence on the human community

The decline of the Sannai-Maruyama community was closely influenced by cyclic climatic changes, indicated by SST changes with an amplitude of 1.5–2.0 °C and a cycle duration of 1.0–2.0 kyr during the Holocene. The human settlement at the Sannai-Maruyama site was established at 5.9 cal kyr BP Aridification of the climate in the great river valley south of 35°N in western Eurasia began in 5.8–5.7 cal kyr BP (Yasuda et al., 2004). Climatic deterioration during 5.8–5.7 cal kyr BP in East Asia has been indicated by an analysis of annually laminated sediments in Lake Tougou (Kato et al., 2003). This synchronous global climatic change significantly affected the rise of ancient civilizations such as those in Mesopotamia, Egypt, the Indus Valley, and along the Yangtze River (Yasuda et al., 2004).

In contrast, the decline of several civilizations has been reported around 4.0–4.3 cal kyr BP This simultaneous decline is considered to have been a consequence of a severe climate deterioration in Eurasia at about 4.2–4.0 cal kyr BP (Yasuda et al., 2004). The Yangtze River settlement seems to have suddenly expanded about ~4.5 cal kyr BP, becoming a megalopolis, but then declined at ~4.0 cal kyr BP (Yasuda et al., 2004). The $\delta^{18}O$ values of a Dongge Cave stalagmite showed that the intensity of the Asian Monsoon decreased greatly in 4.4–4.0 cal kyr BP (Wang et al., 2005), which supports the inference that an abrupt hydrological change might have been responsible for the collapse of the Neolithic culture in central China at ~4.0 cal kyr BP (Wu and Liu, 2004). Strongly enhanced aridity at this time, a main feature of the Indian monsoon as recorded in western China (Hong et al., 2003), is in phase with a Mesopotamian dry event in western Asia (~4.1 cal kyr BP) (deMenocal, 2001). This sudden aridification may be related to the onset of cooler SSTs in the North Atlantic (deMenocal, 2001). Therefore, the simultaneity of these declines might be attributable to climatic cooling or aridification on a global or regional scale.

During the Holocene, the global climate has been generally stable (except at 8.2 cal kyr BP). However, this study shows that even a relatively small fluctuation of atmospheric temperature or SST (~2 °C) can have a great impact on human communities. Climatic cooling might have caused decreases in the population in all Jomon people throughout Japan, as well as the declines of the northern Mesopotamian and Yangtze River civilizations. This lesson might be applicable to modern human society. The Intergovernmental Panel on Climate Change (IPCC; http://www.ipcc.ch/about/about.htm) has reported that, according to some scenarios, the global mean temperature might rise by as much as 2 °C in the next century. Of course, modern human society is highly sophisticated.

However, agriculture is still much influenced by the natural climate. A temperature rise of ~2 °C is likely to have a great impact on certain areas of human activity, despite the sophistication of contemporary society.

5. Conclusions

The establishment of the Sannai-Maruyama settlement can be attributed mainly to a great increase in the food supply under warm climatic conditions, whereas the decline of the settlement may have been determined primarily by climatic cooling (2 °C), which caused both a reduction in the terrestrial food supply and the onset of severe winters. Synchronization of the decline of civilization between the Sannai-Maruyama and north Mesopotamia and along the Yangtze River around 4.0–4.3 cal kyr BP could have been affected by regional to global scale of climatic change.

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